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AUTOMATED RENDEZVOUS AND PROXIMITY OPERATIONS
TECHNIQUES FOR RENDEZVOUS AND CLOSE-IN OPERATION
AND FOR SATELLITE SERVICING

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INTRODUCTION

- o BACKGROUND
- o TEN YEAR TRAFFIC MODEL
- o REFERENCE TARGET VEHICLES REQUIREMENTS
- o ACTIVE VEHICLES
- o SOFT DOCKING SYSTEM
- o NAVIGATION SENSORS
- o G C SENSORS
- o AUTOMATED CONTROL TECHNIQUES
- o AUTOMATED SCENARIOS AND SOFTWARE OPS MODES
- o AUTOMATED PROXIMITY OPERATIONS TIMELINE EXAMPLE

BACKGROUND

"DEVELOPMENT OF AUTOMATED RENDEZVOUS AND PROXIMITY
OPERATIONS TECHNIQUES FOR RENDEZVOUS AND CLOSE-IN
OPERATIONS AND SATELLITE SERVICING"

TYPE: RTOP

OBJECTIVES: TO DEVELOP FREEFLYER AND ORBITER FLIGHT PROFILES
AND RECOMMEND HARDWARE/SOFTWARE REQUIREMENTS
THAT WILL PROVIDE AN AUTOMATED RENDEZVOUS,
STATION KEEPING, AND DOCKING CAPABILITY

TEN YEAR TRAFFIC MODEL

- A SURVEY OF THE MOST LIKELY RENDEZVOUS TARGETS WAS CONDUCTED USING GRUMMAN'S "SATELLITE AND SERVICES USER MODEL."
- INPUT DATA FOR DEVELOPING THE SATELLITE USER MODEL INCLUDED:
 - NASA 5 YEAR PLAN (1981 - 1985)
 - STS FLIGHT ASSIGNMENT BASELINE
 - BATTELLE LOW ENERGY MISSION MODEL
 - FUTURE PLANNING DOCUMENTS (LSTA, OSS, ETC)
 - OAST SPACE SYSTEMS TECHNOLOGY MODEL
 - DOD MISSION CATALOG
 - NORAD SPACECRAFT IDENTIFICATION LISTING
- ALTHOUGH THE MODEL CONTAINS 4 CLASSES OF SATELLITES, ONLY 2 CLASSES WERE USED IN LINCOM'S SURVEY:
 - 1) APPROVED AND FUNDED VEHICLES (A)
 - 2) VEHICLES PLANNED FOR START IN NEXT 5 YEARS (P)

RENDEZVOUS CALENDAR
(FUNDED AND APPROVED SATELLITES)
(DOD SATELLITES NOT INCLUDED)

1983	1984	1985	1986	1987
SPAS p-114	*(CHEM REL MOD)	SPAS LDEF ST	*LANDSAT D" *(CHEM REL MOD) *(ERBS) *(NOAA) ST	(SPAS) *EUVE *(COBE) ST (LDEF) *(NOSS)
1988	1989	1990	1991	1992
LDEF *(NOSS) ST *(NOSS)	(SPAS) ST *(NOSS) *(ERBS)	(LDEF) *(NOSS)	(SPAS) *(ERBS) (ST) (LDEF) *(NOSS)	LDEF *(NOSS) (ST)

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SCHEDULED EVENTS FROM 1983 THROUGH 1992

FUNDED AND APPROVED MISSIONS

	DEPLOY MISSIONS		SERVICE MISSIONS		RETRIEVAL MISSIONS	
	USER IDENTIFIED	ASSUMED	USER IDENTIFIED	ASSUMED	USER IDENTIFIED	ASSUMED
ORBITER ALONE	2	3	--	--	2	3
ORBITER + OMS KIT(S)	4	1	4	5	4	--
ORBITER + LEO PROP PACKAGE	8	6	--	5	2	9

OF ALL THE "APPROVED" USER IDENTIFIED RENDEZVOUS' (SERVICE OR RETRIEVAL EVENTS) SCHEDULED FOR THE NEXT TEN YEARS:

- 2 (17%) CAN BE PERFORMED BY AN ORBITER WITH INTEGRAL OMS PERFORMANCE
- 8 (67%) CAN BE PERFORMED BY AN ORBITER WITH OMS KITS
- 2 (17%) MUST BE PERFORMED VIA LEO PROPULSION PACKAGES

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RENDEZVOUS CALENDAR

(SATELLITES PLANNED BY PROGRAM OFFICE FOR START IN NEXT 5 YEARS)

(DOD SATELLITES NOT INCLUDED)

1983	1984	1985	1986	1987
*SOLAR MAX			*LANDSAT D" SUBSAT FAC	SUBSAT FAC *(MAGSAT) SASP PWR MOD *LANDSAT D" *(XRAY TIME) *(ICE/CLIM EXP)
1988	1989	1990	1991	1992
SASP PWR MOD AXRA GRAV PROB (COASTAL SAT) *(NOAA) *(H2O DUAL) *UPPER ATMOS *(HI ENGY) *(LANDOPS) *(AWMW) *(EARTH SURV) SUBSAT FAC *LANDSAT D" *XRAY TIME *(ICE/CLIM EXP)	SASP PWR MOD (MAG FIELD SURV) AXRA GRAV PROB (COASTAL SAT) *(NOAA) *UPPER ATMOS *(LANDOPS) *(AWMW) *(EARTH SURV) SUBSAT FAC *LANDSAT D" *(LANDOPS)	SASP PWR MOD (MAG FIELD SURV) (COASTAL SAT) *UARS *(XRAY TIME) *(ICE/CLIM EXP) *(LANDOPS) *(PER) *(ADV THERM) SUBSAT FAC AXRA GRAV PROB *(NOAA) *(H2O DUAL) *(HI ENGY) *(LANDOPS) *(TOPOG EXP)	SASP PWR MOD (COASTAL SAT) *UARS *(ICE/CLIM EXP) *(EARTH SURV) *(OP MET) PWR MOD (MAG FIELD SURV) SUBSAT FAC *(NOAA) *(XRAY TIME) *(LANDOPS) *(AWMW)	SASP PWR MOD AXRA *UARS *(LANDOPS) *(ADV THERM) (COASTAL SAT) *(ICE/CLIM EXP) *(PER)

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SCHEDULED EVENTS FOR 1983 THROUGH 1992
(SATELLITES DESIGNATED BY PROGRAM OFFICE FOR START IN NEXT 5 YEARS)

	DEPLOY MISSIONS		SERVICE MISSIONS		RETRIEVAL MISSIONS	
	USER IDENTIFIED	ASSUMED	USER IDENTIFIED	ASSUMED	USER IDENTIFIED	ASSUMED
ORBITER ALONE	16	6	9	3	6	2
ORBITER + OMS KIT(S)	2	1	14	4	3	--
ORBITER + LEO DROP PACKAGE	26	10	9	22	3	14

OF ALL THE "PLANNED" USER IDENTIFIED RENDEZVOUS' (SERVICE OR RETRIEVAL EVENTS) SCHEDULED FOR THE NEXT TEN YEARS:

- 15 (34%) CAN BE PERFORMED BY AN ORBITER WITH INTEGRAL OMS PERFORMANCE
- 17 (39%) CAN BE PERFORMED BY AN ORBITER WITH OMS KITS
- 12 (27%) MUST BE PERFORMED VIA LEO PROPULSION PACKAGES

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RENDEZVOUS TRAFFIC
SUMMARY TABLE

YEAR	FUNDED OR APPROVED	PLANNED	TOTAL	LEO PROPULSION
1983	1	1	2	1
1984	1	1	2	2
1985	3	-	3	-
1986	5	2	7	5
1987	6	7	13	7
1988	4	14	18	10
1989	4	14	18	9
1990	2	19	21	13
1991	5	15	20	11
1992	3	10	13	7
TOTAL	34	83	117	65

TARGET VEHICLE REQUIREMENTS

- REPRESENTS A LARGE CLASS OF SIMILAR TARGET VEHICLES
- ACTIVE ATTITUDE CONTROL SYSTEM
- PASSIVELY COOPERATIVE
 - REQUIRED RETRIEVAL COMPONENTS IMPLEMENTED PRIOR TO LAUNCH
 - RETRIEVAL COMPONENTS ARE EXTERNAL TO SATELLITE SYSTEMS
 - RETRIEVAL COMPONENTS REQUIRE ONLY A PHYSICAL ATTACH POINT
- FIRM RENDEZVOUS REQUIREMENT

TARGET VEHICLES SELECTED

- LEO - LANDSAT/MMS
- HEO - GPS (NO RENDEZVOUS REQUIREMENT)
- GEO - TDRSS (NO RENDEZVOUS REQUIREMENT)

ACTIVE VEHICLES

- TELEOPERATOR MANEUVERING SYSTEM (TMS)/VOUGHT
- ORBITAL TRANSFER VEHICLE (OTV)/BOEING/GENERAL DYNAMICS
- MANNED ORBITAL TRANSFER VEHICLE (MOTV)/GRUMMAN
- MANEUVERABLE TELEVISION SYSTEM (MTV)/JSC/LOCKHEED
- SPACE PLANE/USAF/SRI

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SOFT DOCKING SYSTEM

- A "SOFT DOCKING" SYSTEM IS REQUIRED FOR DOCKING OPERATIONS
- A "SOFT DOCKING" SYSTEM REQUIRES ZERO VELOCITY TO EFFECT CAPTURE
- THE RMS SNARE TYPE END EFFECTOR IS AN EXAMPLE OF A LIGHT WEIGHT SOFT DOCKING SYSTEM
- THE SOFT DOCKING SYSTEM WILL "DRIVE" THE DOCKING SENSOR REQUIREMENTS
- A PRELIMINARY SET OF SOFT DOCKING SYSTEM REQUIREMENTS WERE GENERATED BY JIM JONES/JSC/EW4 AND EARL CRUM/JSC/EW4 IN SUPPORT OF THIS STUDY

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ONBOARD GN&C SENSOR REQUIREMENTS

SENSOR PARAMETER	INERTIAL ATT				REL ATT				RELATIVE POSITION			
	PHASE											
	Rendezvous		X		X							
	Long-range Stationkeeping				X						X	
	\bar{V} Approach to 300'				X						X	
	\bar{V} Sk, at 300				X						X	
	Inertial Sk at 300'		X								X	
	Flyaround		X		X						X	
	Inspection								X		X	
	Docking								X		X	

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G&C SENSORS

- ACCELEROMETERS
- GYROS

- WHEELS

- LASERS - A LASER IRU THEORETICALLY OFFERS
SEVERAL ADVANTAGES OVER A STANDARD
STRAP-DOWN OR GIMBALED PLATFORM IRU:

- 1) SUPERIOR RELIABILITY
- 2) NO MOVING PARTS
- 3) LOWER UNIT COST
- 4) LEAST OPERATIONALLY COMPLEX

AUTOMATED CLOSE-IN CONTROL TECHNIQUE

ROTATION - ROTATION DAP - RCS

TRANSLATION - TRANSLATION DAP - RCS

ROTATION ALWAYS LEADS TRANSLATION

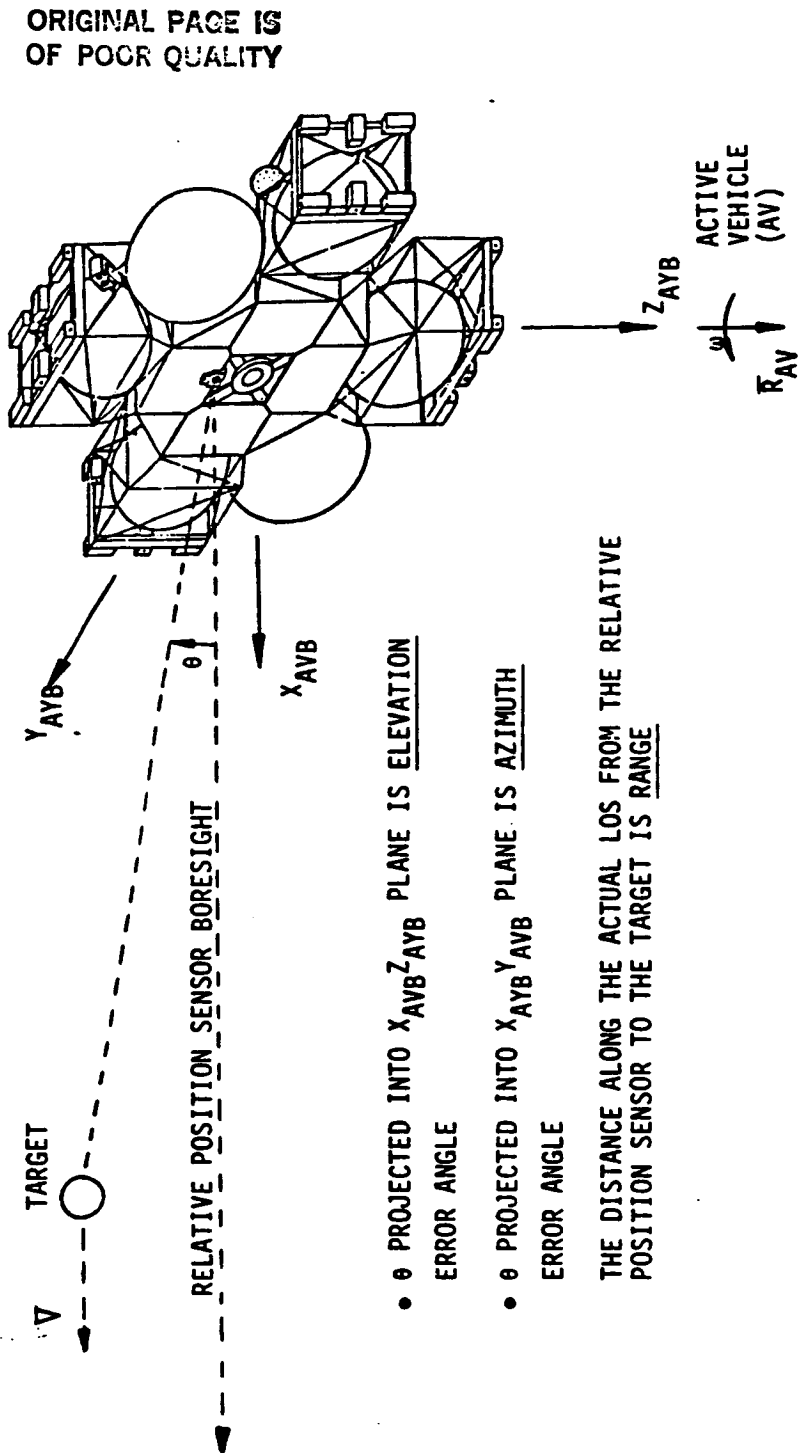
EXAMPLES

- ▽ STATIONKEEPING
- FLYAROUND
- FINAL APPROACH

V STATIONKEEPING

AV ATTITUDE CONTROL SYSTEM IS TRACKING LVLH FRAME SUCH THAT XBODY IS POINTED ALONG \bar{V}_{AV} AND YBODY IS POINTED ALONG \bar{H}_{AV} .

AV TRANSLATION CONTROL SYSTEM IS MAINTAINING ELEVATION, AZIMUTH ERROR ANGLES AND RANGE TO TARGET VEHICLE CORNER REFLECTOR WITHIN SPECIFIED LIMITS.



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AUTOMATED SCENARIOS

- REFERENCE MISSIONS

- DELIVERY
- RETRIEVAL
- SERVICING
- REMOVAL
- TRANSFER

- COMMON OPERATIONS - COMMON OPERATIONS CAN BE USED TO CONSTRUCT THE TOTAL SET OF RENDEZVOUS OPERATIONS AND CAN BE THOUGHT OF AS OPERATIONAL SEQUENCES. EACH OPERATIONAL SEQUENCE CONTAINS THE NECESSARY SET OF MAJOR MODES AND FUNCTIONS TO ACCOMPLISH THE REQUIRED OPERATION.

- RNDZ MANEUVER TARGETING
- MANEUVER EXECUTE
- COAST
- BRAKING
- STATION KEEPING
- FLYAROUND
- FINAL APPROACH
- DOCKING
- SEPARATION

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SOFTWARE OPS MODES

- COMMON OPERATIONS ORIGINALLY CONCEIVED IN THE DEVELOPMENT OF AUTOMATED RENDEZVOUS SCENARIOS HAVE BEEN ORGANIZED INTO "OPS MODES" AND FURTHER SUBDIVIDED INTO MAJOR MODES."

OPS MODE	1XXX	SEQUENCER ACTIVE
OPS MODE	OXXX	TERMINATE SEQUENCER BUT CONTINUE WITH CURRENT MM (MAY BE USED WITH OPS MODES 400, 700, OR, 900)
OPS MODE	200	RENDEZVOUS (RUNS CONCURRENTLY WITH OPS MODES 400 OR 800)
	MM 201	ORBIT TARGET (LAMBERT OR CW)
	MM 202	MNVR EXEC (LAMBERT OR EXTERNAL ΔV)
OPS MODE	300	BRAKING
	MM 301	TO STANDOFF - DRIVES $\dot{e}, \dot{a}, \dot{r}$, TO ZERO AT $e = 0$
	MM 302	INERTIAL LOS TO TARGET - (ALWAYS ALONG FIXED LOS)
	MM 303	LVLH LOS TO TARGET - (ALWAYS ALONG FIXED LOS)
OPS MODE	400	STATIONKEEPING
	MM 401	INERTIAL
	MM 402	LVLH
	MM 403	LVLH/REL NAV
	MM 404	RELATIVE
	MM 405	SUB ORBIT
	MM 406	SUB ORBIT/REL NAV
OPS MODE	500	FINAL APPROACH/SEPARATION
	MM 501	FINAL APPROACH/SEPARATION
OPS MODE	600	FLYAROUND
	MM 601	INERTIAL
	MM 602	LVLH
	MM 603	CONSTANT RATE
OPS MODE	700	DOCKING
	MM 701	APPROACH
	MM 702	SEPARATION
OPS MODE	800	COAST
	MM 801	INERTIAL ATTITUDE HOLD
	MM 802	LVLH ATTITUDE HOLD
	MM 803	INERTIAL MANEUVER
	MM 804	LVLH MANEUVER
	MM 805	TARGET TRACK
	MM 806	TARGET TRACK/REL NAV
	MM 807	ROTATION
	MM 808	FREE DRIFT

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A "SEQUENCER" IS REQUIRED TO:

- 1) PERFORM PREPLANNED SEQUENCE OF MAJOR MODE TRANSITIONS
- 2) ENSURE PROPER DATA TRANSFER AND INITIALIZATION BETWEEN MAJOR MODE TRANSITIONS
- 3) ASSEMBLE NECESSARY HARDWARE/SOFTWARE SYSTEMS
- 4) PROVIDE FOR THE MAN/MACHINE INTERFACE

SOME SOFTWARE NOTES . . .

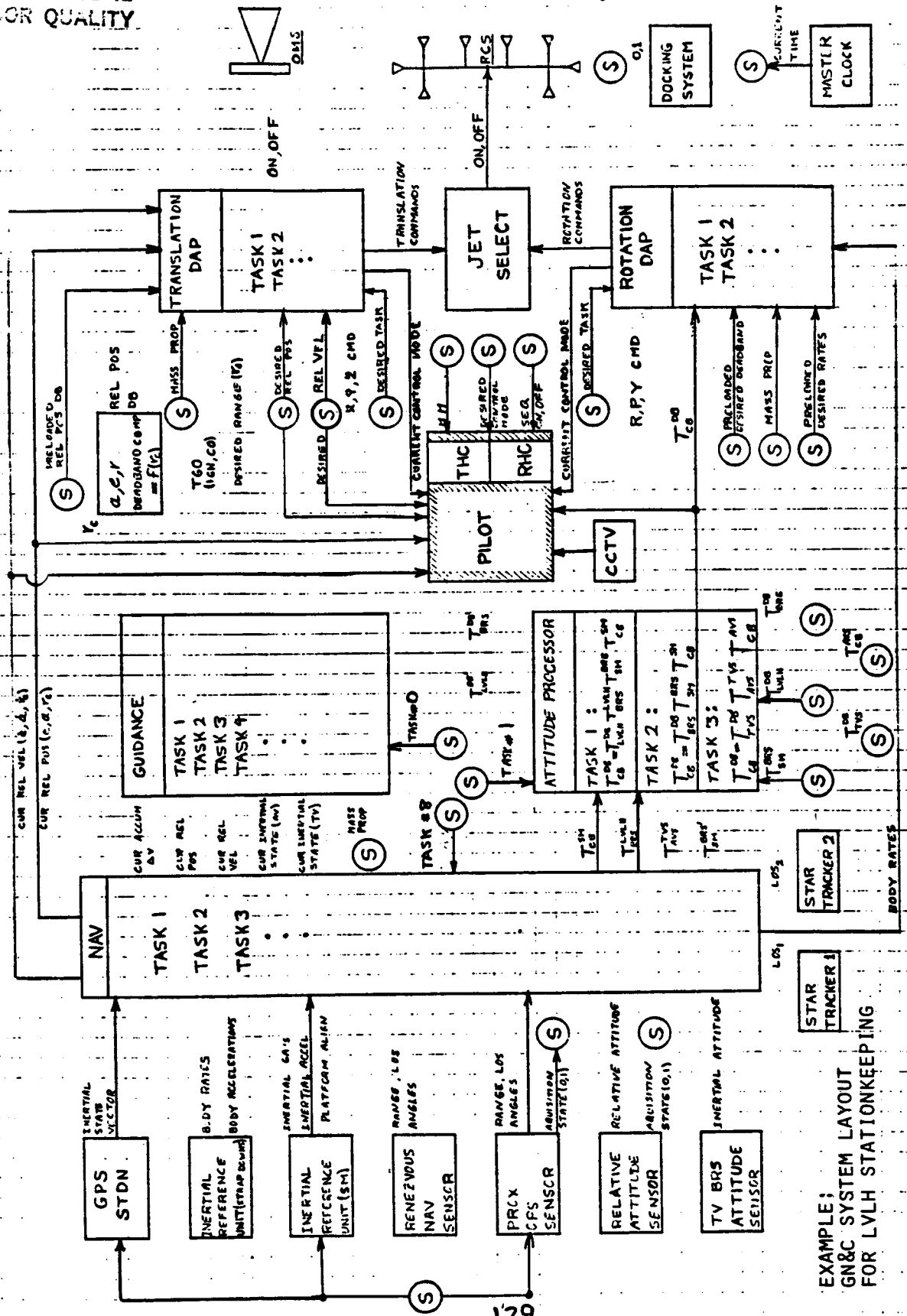
- ANY GIVEN MISSION WOULD CONSIST OF A SUBSET OF THE ABOVE MAJOR MODES
 - ALL CURRENT AND CONCEIVED RENDEZVOUS/PROX OPS MISSIONS CAN BE PERFORMED WITH THE PROPER SEQUENCE OF THE LISTED MAJOR MODES.
 - A LARGE PORTION OF THE SOFTWARE REQUIREMENTS FOR THE LISTED MAJOR MODES ALREADY EXIST IN THE LEVEL C GN&C ON-ORBIT GUIDANCE FSSR.
 - SYSTEM DIAGRAMS FOR EACH MAJOR MODE HAVE BEEN GENERATED. THE SYSTEM DIAGRAMS SHOW THE REQUIRED SYSTEM COMPONENTS, THE BASIC SYSTEM REQUIREMENTS, AND THE DATA FLOW BETWEEN COMPONENTS.
- FOLLOWING IS A SELECTED SYSTEM DIAGRAM AS AN EXAMPLE.

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MM1402 LV LH STATION KEEPING

MM1402 GNC SYSTEM LAYOUT

AUTONOMOUS RENDEZVOUS, PROXIMITY OPERATIONS, DOCKING

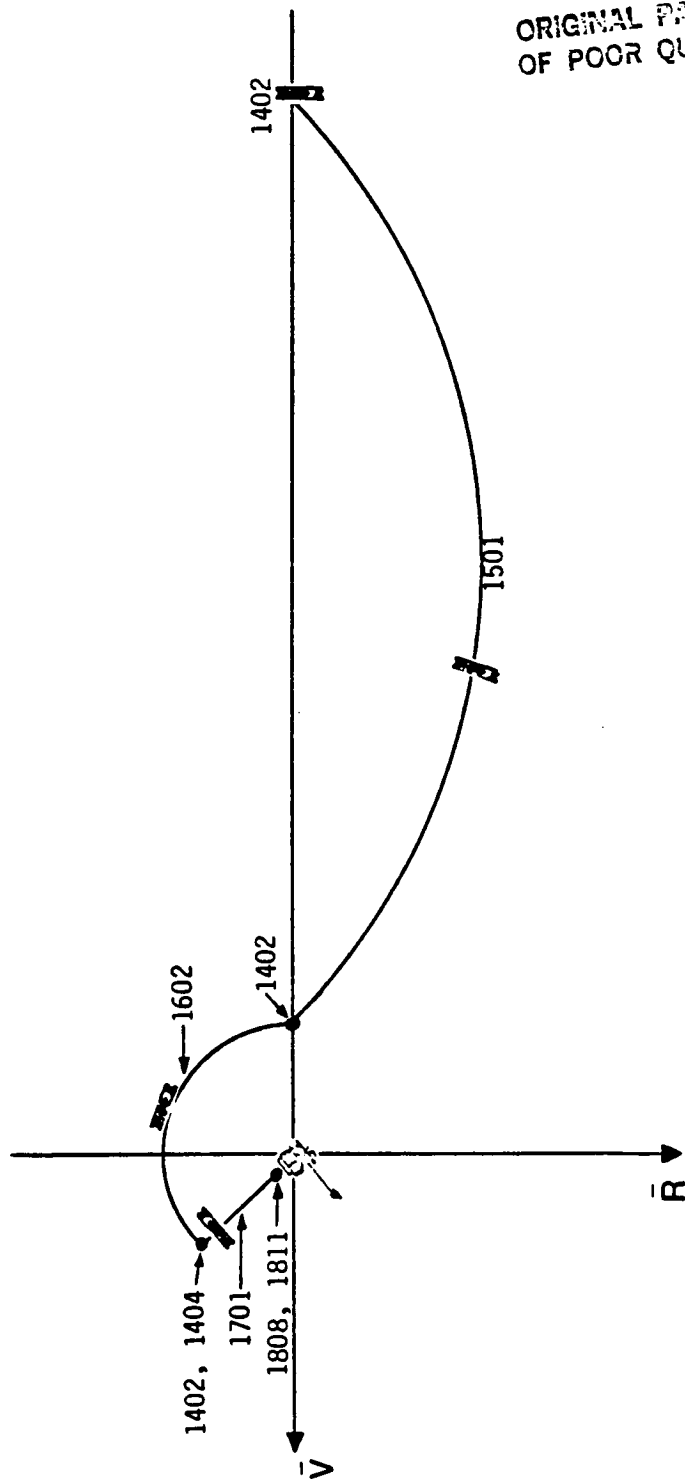


EXAMPLE;
GN&C SYSTEM LAYOUT
FOR LV LH STATION KEEPING

- RESULTS OF MAJOR MODES CONCEPT . . .
 - EASILY IDENTIFIES THE SPECIFIC ITEMS THAT NEED TO BE WORKED, BOTH HARDWARE AND SOTWARE, AS A FUNCTION OF MISSION PHASE.
 - PROVIDES OVERALL SYSTEM DEFINITION
 - SERVES AS A FRAMEWORK FOR ORGANIZING DETAILED SYSTEM REQUIREMENTS

TIMELINE EXAMPLE
AUTOMATED PROXIMITY OPERATIONS

RELATIVE MOTION PLOT
FINAL APPROACH, FLYAROUND, DOCKING
LVLH TARGET VEHICLE



TIMELINE AUTOMATED PROXIMITY OPERATIONS

AUTOMATED OPERATIONS				GROUND OPERATION
TIME	EVENT	MM	DESCRIPTION	CONDITION
01:30	LVL H SK	1402	LVLH STATIONKEEPING (V)	COMPLETION OF TPF MANEUVER
01:40	FINAL APP	1501	FINAL APPROACH INITIATION	MM1402 + 10 MIN.
01:50				
02:00	LVLH SK	1402		LOCAL HORIZONTAL ELEVATION ANGLE GOES THROUGH 0°

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TIMELINE AUTOMATED PROXIMITY OPERATIONS

AUTOMATED OPERATIONS				GROUND OPERATION
TIME	EVENT	MM	DESCRIPTION	CONDITION
02:00				
02:10	FLY ARND	1602	FLYAROUND TO DESIRED LVLH ATTITUDE	MM1402 + 10 MIN.
	DOCKING SENSOR ACQ			
02:20	LVLH SK	1402	LVLH STATIONKEEPING	LVLH DOCKING ATTITUDE ACHIEVED
	REL SK	1404		DOCKING SENSOR ACQ + (MM1402 + 2 MIN
02:30	DOCKING	1701	DOCKING APPROACH	MM1404 + 5 MIN.

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TIMELINE AUTOMATED PROXIMITY OPERATIONS

AUTOMATED OPERATIONS				GROUND OPERATION
TIME	EVENT	MM	DESCRIPTION	CONDITION
02:30				
	SOFT DOCK	1808	COAST (UNDOCKED FREE DRIFT)	
02:40	HARD DOCK	1811	COAST (DOCKED INERTIAL HOLD)	
02:50				
03:00				
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CONCLUSIONS

- ALTHOUGH THE U.S. HAS NEVER PERFORMED AN AUTOMATED RENDEZVOUS AND DOCKING, MOST OF THE "PIECES" REQUIRED TO BUILD AN AUTOMATED SYSTEM CURRENTLY EXIST.

MAJOR EXCEPTIONS ARE:

- CLOSE IN REL ATT SENSOR SYSTEM
 - CLOSE IN REL POS SENSOR SYSTEM
 - TRANSLATION DAP SOFTWARE
 - SEQUENCER SOFTWARE
 - SOFT DOCKING SYSTEM
- AUTOMATED RENDEZVOUS TECHNIQUES AND OPERATIONS ARE GENERIC IN NATURE AND APPLICABLE TO MANNED AS WELL AS UNMANNED SYSTEMS